Shallow-Water Propagation

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N000140510155
(OA Graduate Traineeship – Jon M. Collis)
http://www.math.rpi.edu/www/ocean_acoustics

LONG-TERM GOALS

Develop methods for propagation and coherence calculations in complex shallow-water environments, determine their capabilities and accuracy, and apply them for modeling and understanding data.

OBJECTIVES

(A) Treat propagation from narrowband and broadband sources over elastic and poro-elastic sediments, and incorporate realistic bathymetric, topographic, and geoacoustic variations.

(B) Analyze and interpret acoustic data, quantify effects of random environmental and experimental variability, and efficiently determine field statistics for intensity and coherence.

APPROACH

(A) Develop high accuracy PE techniques for applications to shallow-water sediments, accounting for heterogeneities and anisotropy. Treat range dependence and layering by coordinate rotation and single scattering methods. Benchmark results using data and calculations from other methods.

(B) Develop environmental representations for ocean and geoacoustic variability using data and parametric models. Perform acoustic field calculations with PE, normal mode, and perturbation methods. Use computational results and data analysis to specify propagation mechanisms.

- Principal collaborators are: Rensselaer graduate students and recent graduates; Dr. Michael Collins (NRL), for model development; and Dr. William Carey (BU), Dr. Allan Pierce (BU), Dr. James Lynch (WHOI), and Dr. Mohsen Badiey (Delaware), for data analysis and interpretation.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2006**	2. REPORT TYPE	3. DATES COVERED **00-00-2006 to 00-00-2006**

4. TITLE AND SUBTITLE **Shallow-Water Propagation**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Rensselaer Polytechnic Institute,110 Eighth Street,Troy,NY,12180-3590**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**9**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

WORK COMPLETED

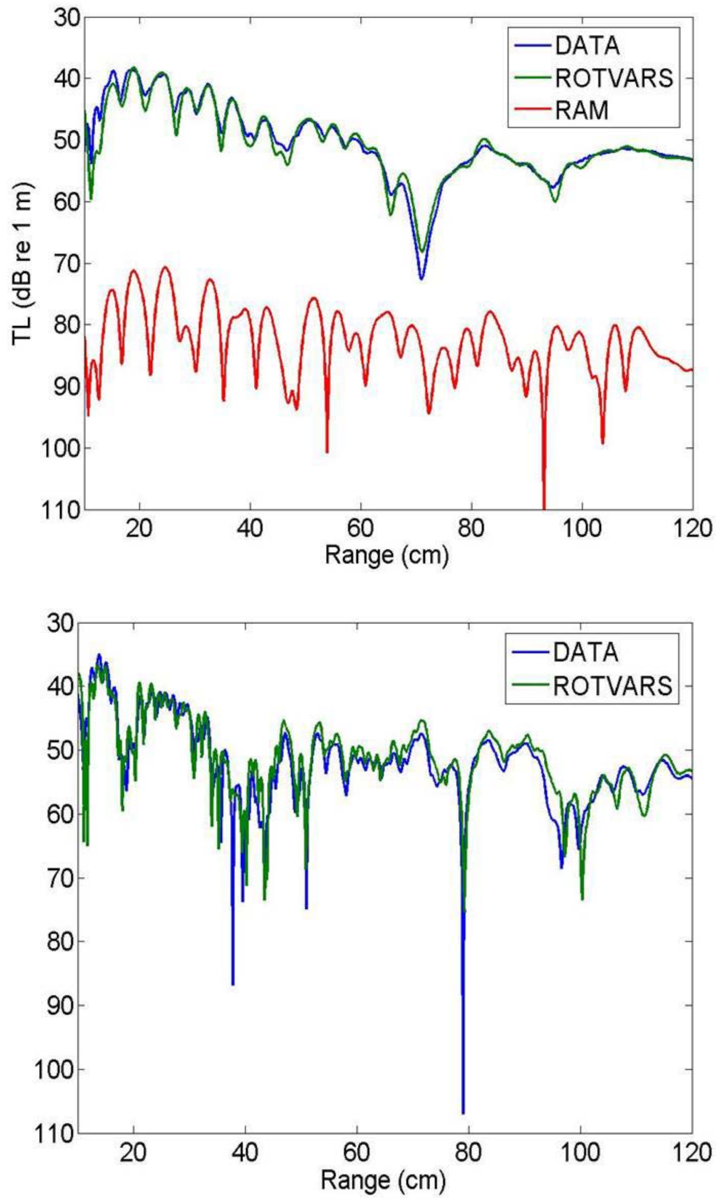
(A) A long-standing problem of efficiently finding accurate solutions for ocean seismo-acoustic problems with range-dependent bathymetry is resolved [1], by using a PE approach with coordinate rotations at locations of slope changes. The method is extended [2] to elastic media with topographic variations that occur in shelf and beach problems having relatively large changes in interface depths, and examples show Scholte waves which evolve into Rayleigh waves. Calculations that verify the accuracy of the method include comparisons with another technique based on a coordinate transformation procedure [3], which handles substantial variations in interface depths provided the rate of slope change remains small. Another essential capability is treating range-dependent interfaces in sediments with realistically large changes in elastic properties and interface slopes, and a new approach using the single scattering approximation [4] accomplishes this efficiently for sediment interfaces that are parallel to the bathymetry. The two techniques in [1] and [4] are combined in a breakthrough method [5] that for the first time allows solution of ocean seismo-acoustics propagation problems with range-dependent bathymetry and variable-depth sediment layers. Calculations from our elastic model with coordinate rotations show excellent agreement in comparisons [6] with high-quality laboratory data from propagation over an elastic slab. The first propagation model that can handle range dependence of transversely isotropic poro-elastic sediments [7] has an improved method for specifying its input parameters. Another method [8] permits increased efficiency for kHz frequencies by combining key components of two previous split-step algorithms and is useful where environmental variations are relatively small. Calculations of acoustic particle velocity and vector intensity are efficiently performed using PE methods [9] and show the types of information available from these fields.

(B) New results [10] demonstrate how nonlinear frequency dependence of the intrinsic sediment attenuation, along with water SSPs and bathymetry, control the accuracy of comparisons between propagation calculations and mid-frequency data from two experiments on the New Jersey shelf near the SW06 site. Calculations of modal attenuation coefficients that account for this frequency dependence are compared with data from the Gulf of Mexico and near Nantucket [11], and their sensitivity to water SSPs is quantified. A parametric description of relatively simple shallow ocean waveguides permits development of analytical expressions for modal attenuation coefficients [12] and interpretations of observations. The nonlinear frequency dependence of sediment attenuation must be included for good agreement [13] between calculations of broadband intensity variations, which arise from geoacoustic uncertainties, and data from a 1992 experiment at the New Jersey AGS. A mechanism that was previously described theoretically, of adiabatic horizontal energy refraction between wave fronts of solitons, is shown to occur during the SWARM95 experiment [14] by comparing data and calculations for the intensity time behavior. In contrast, fully three-dimensional propagation calculations show that horizontal mode coupling from interactions of soliton wave fronts arises [15] depending on the soliton strengths and orientations. For acoustic propagation nearly parallel to a nonlinear wave front, the influence of the frontal degradation that usually develops as the wave evolves is modeled by a variable-coefficient diffusion equation for modal amplitudes [16]. Calculations using data from the ACT III experiment in the Strait of Korea [17] show that nonlinear frequency dependence of the upper sediment attenuation not only captures the key features of four independent data sets but also permits determination of useful estimates of transverse coherence lengths. If these lengths are calculated under conditions for adiabatic normal modes [18], strong variation occurs with horizontal direction when the environmental correlation functions have anisotropy or heterogeneity as a result of processes such as internal waves.

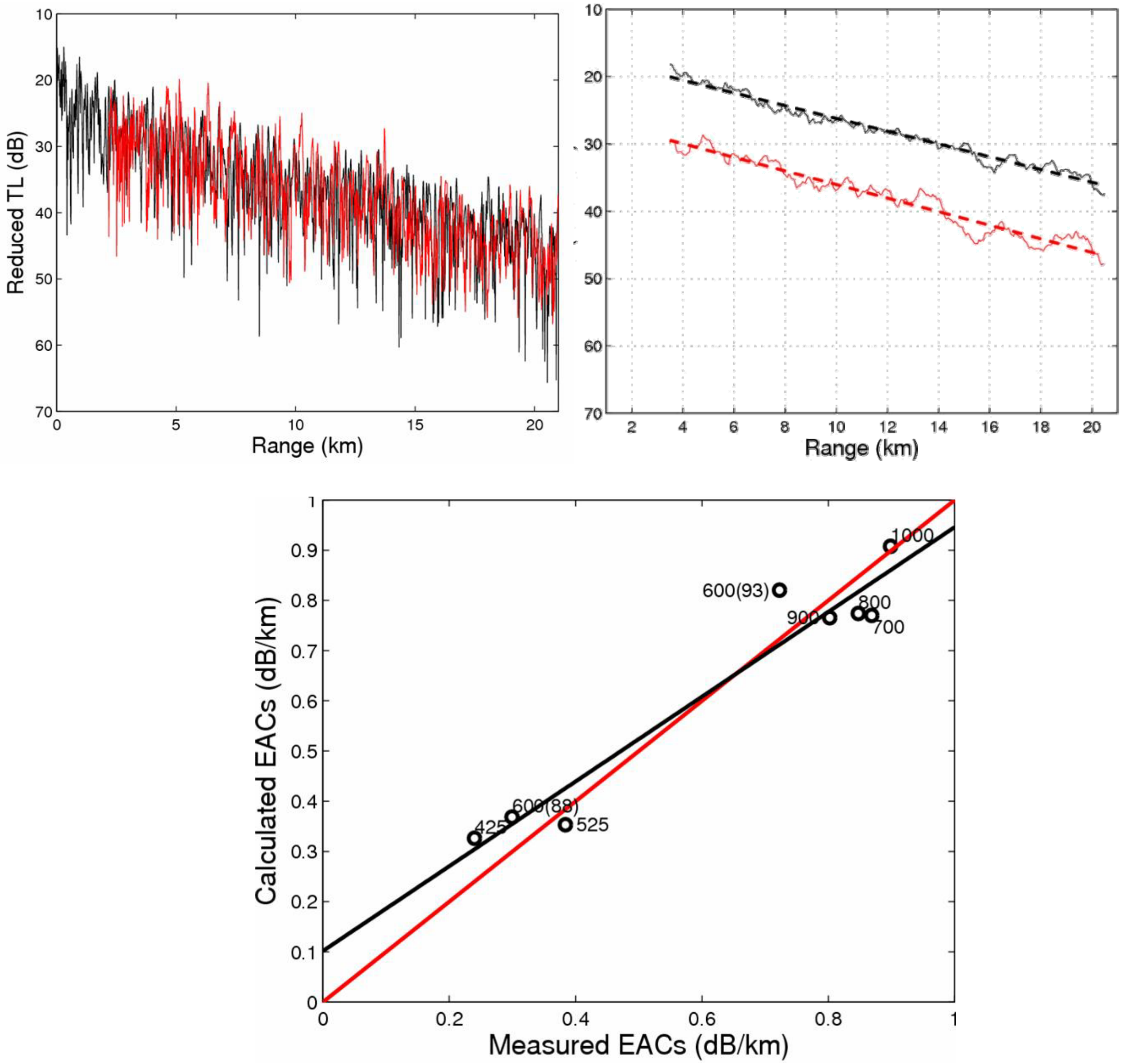
RESULTS (from two selected investigations)

(A) One essential capability for ocean acoustics applications is propagation over and through range-dependent elastic sediments. Accurate and efficient treatment of these problems, which are notoriously more difficult than calculations for fluid-model sediments, is important in itself and is necessary progress toward handling more complex sediments. The first required step is our PE formulation in which the dependent variables are the range derivative of the horizontal displacement u_r and the vertical displacement w. The next step is our method with coordinate rotations at ranges where bathymetry slopes occur, which leads to an efficient procedure [1] valid over a wide range of values for slopes and elastic parameters. Accuracy checks of this method for simple test problems show better results than the standard procedure, which approximates bathymetry slopes by stair steps and uses a simplified energy-conservation condition at vertical interfaces. A critical question is how well the new propagation model performs in comparisons with experimental measurements. Strenuous tests are available using very high quality measurements from a model experiment of propagation over an elastic slab in a large water tank at NRL [6]. Single-frequency propagation loss curves with the slab in a sloping configuration are shown as blue curves in **Figure 1**. The upper panel shows that the green curve, from the new method using frequency/length scaling factor of 1000, provides a strikingly close comparison with data. The red curve, from a fluid-model bottom and displaced for clarity, has completely mismatched the pattern phase and amplitude behavior. The lower panel, for a frequency three times larger and many more propagating modes, shows remarkable agreement between the modal interference patterns. We conclude from these and related results that the new propagation model provides a powerful and efficient tool for high accuracy calculations in range-dependent ocean seismo-acoustic waveguides.

(B) Propagation predictability at medium frequencies remains a critical problem in shallow water waveguides. Particular interest is in the relatively widespread regions with moderate range dependence and sandy-silty sediments. The intrinsic sediment attenuation leads to an overall degradation of transmission loss with range, as is well known, but it is essential to quantify the connection. When high quality broadband measurements are available, propagation modeling can unravel the interactions, not only at lower frequencies where loss patterns can often be modeled in detail but also at moderate frequencies with many propagating modes [10]. A useful metric is an effective attenuation coefficient (EAC) for the reduced transmission loss, determined by suitable range and depth averages of measurements and PE calculations. Results for 700 Hz from the 1993 ACT II experiment are displayed in the upper panel of **Figure 2.** The left panel shows reduced loss, with measurements in red and calculations in black. The right panel shows range-window-averaged loss and linear fits (with calculations displaced), the slopes of which are the EACs. Critical parameters for the calculations are the frequency-power exponent and near-bathymetry value of the upper layer sediment attenuation, along with the water sound speeed and bathymetry profiles. The lower panel is a scatter plot of measured and calculated EACs for frequencies above 400 Hz in the ACT II and 1988 New Jersey Shelf experiments. The best fit line, which has slope one if the calculations exactly model the measurements, is sensitive to values of the critical parameters. Consistent with analyses for other sandy-silty locations, the attenuation frequency-power exponent and surface values are in the ranges [1.8, 2.0] and [0.33, 0.35] dB/m. We conclude that significant nonlinear frequency dependence of the upper sediment attenuation is necessary, and that relatively few site-specific parameter values have major effects on the loss degradation at medium frequencies.



<u>Figure 1</u>. Propagation in range-dependent oceanic waveguides over elastic sediments is treated efficiently and accurately by a new PE approach that uses coordinate rotations at ranges where the bathymetry slope changes. High-quality data obtained from a tank experiment at NRL provides transmission loss curves, shown for source and receiver depths 1.5 and 6.3 cm, for propagation over an elastic slab sloped from 13.3 to 4.5 cm depth on a 120 cm range. The slab has nominal compressional and shear sound speeds of 2290 and 1050 m/s, attenuations of 0.76 and 1.05 dB/λ , and density 1.378 g/cm^3. The blue curves are processed data and the green curves are calculations. <u>Upper panel</u>: For 100 kHz, the amplitudes and phases of the loss patterns for data and calculations show excellent agreement. The red curve displayed (and displaced 30 dB) is for a fluid-model bottom, which differs strongly in all respects from the data. <u>Lower panel</u>: For 300 kHz with many more propagating modes, there is a remarkable correspondence between fine details of the interference patterns for data and calculations.



<u>Figure 2</u>. Transmission loss degradation in regions with moderate range dependence and sandy-silty sediments is modeled effectively by accounting for water profiles, bathymetry, and key features of the upper sediment attenuation. <u>Upper panels: (left)</u> Transmission loss curves with cylindrical spreading removed; PE calculations (red) and measurements from 1993 ACT II experiment (black), to range 21 km and at depth 53 m. Highly oscillatory interference patterns occur from many propagating modes. <u>(right)</u> Range-averaged (1 km window) and depth-averaged (three receivers) reduced loss curves and best linear fits, with calculations displaced 10 dB. The slopes are the effective attenuation coefficients (EACs); 1.01 (measured) and 0.95 (calculated). <u>Lower panel</u>: Scatter plot of measured and calculated EACs (with frequencies labeled) from ACT II and the 1988 New Jersey Shelf experiment. Calculations use sediment attenuation frequency-power exponent 1.8 and surface value 0.35. The best linear fit to the points is the line (black) with slope 0.85 and intercept 0.10, which is close to the exact-model line (red).

IMPACT/APPLICATIONS

New or improved capabilities for handling shallow-water sediment physical properties, including layering, elasticity, porosity, and anisotropy, are made available for propagation predictions. Sediment interfacial variability, including range-dependent bathymetry and layer boundaries, can be treated accurately in calculations. Efficient determination of intensity and coherence statistics resulting from environmental fluctuations and experimental variability is feasible. Data analyses and comparisons allow specification, for experimental measurements and for applications, of the relative significance of a variety of physical mechanisms: linear versus nonlinear frequency dependence of attenuation, water column versus bathymetric variability, and vertical versus horizontal mode coupling due to internal solitons and bathymetry. Results from modeling and data analyses of several experiments, including the ACT series, the New Jersey Shelf experiments, and SWARM, are partly aimed toward improving shallow-water sonar systems and predictions. New propagation model implementations, analysis tools, and data representation techniques are being distributed to university, laboratory, and research and development groups, including technical personnel at NWSC-PC and NAWC-PAX.

RELATED PROJECTS

- Ongoing work with Dr. Michael Collins includes completion of a research monograph on state of the art PE models and applications [19], for which the primary research technical issues have now been resolved. Benchmark calculations [20] show the efficient performance of our propagation model for low frequency range-dependent problems in elastic media. A new PE solution [22] for gravity wave propagation in fluids demonstrates the influence of buoyancy and advection effects.

- Additional research with Dr. James Lynch, Dr. Mohsen Badiey, and their colleagues is concerned with influences of azimuthal variability in shallow water. Physical mechanisms with interesting consequences that arise from acoustic interactions with internal solitions and fronts are described and illustrated [23]. Heterogeneous sediments with complex stratigraphy that occur in coastal regions can produce cross-range acoustic effects [24].

- Other investigations with Dr. William Carey and Dr. Allan Pierce examine issues related to predictability of narrowband propagation characteristics, including coherence scales and the frequency dependence of sediment attenuation. Analytical approximations which are useful for understanding parameter dependencies are developed for mode functions in shallow water waveguides with summer thermocline conditions [25].

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PUBLICATIONS

- Published [refereed]: [14], [17], [22]
- Accepted [refereed]: [1]
- Submitted [refereed]: [3], [4], [7], [13]
- Proceedings [non-refereed]: [10], [11], [20], [24].